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EFFECT OF VARIATION OF MASS FLOW RATE ON PERFORMANCE OF SOLAR PARABOLIC DISH COLLECTOR WITH DOME-CYLINDRICAL RECEIVER

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ABSTRACT

Solar parabolic dish collector is one of the foremost economical technologies for energy conversion among concentrated solar energy systems. Parabolic dish concentrators use cavity type receivers at their point of focus to convert incident solar radiation into heat energy. Different receivers with cavity type designs were used to determine the thermal performance of solar parabolic dish type concentrators for various applications, such as industrial process heat, thermal power generation and water heating, etc. In the present work, thermal efficiency of parabolic dish collector is analysed with dome-cylindrical type cavity receiver by changing the mass flow rate of water. Experiments are performed on clear and sunny days in the month of April at KLEF (Deemed-to-be-University) [Latitude: 16.5° N, Longitude: 80.6° E].

KEYWORDS: Cavity Receiver, Heat Losses, Parabolic Dish Collectors, Solar Energy, Thermal Efficiency & Thermal Performance

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NOMENCLATURE

A_a	Area of the concentrator, m^2
A_{ab}	Aperture area of the absorber, m^2
A_c	Total receiver internal surface area, m^2
A_o	Outer surface area of the receiver, m^2
A_w	Inner surface area of the receiver, m^2
d	Absorber diameter, *m*
G^*	Solar beam radiation, W
Gr	Grashoff number
g	Acceleration due to gravity, $m\,s^{-2}$
h_{cv}	Convective heat transfer coefficient, $Wm^{-2}K^{-1}$
h_f	Forced convective heat transfer coefficient, $Wm^{-2}K^{-1}$
h_n	Natural convective heat transfer coefficient, $Wm^{-2}K^{-1}$
h_w	Heat transfer coefficient of wind, $Wm^{-2}K^{-1}$
I^*	Direct Radiation, W
K_{air}	Thermal conductivity of air, $Wm^{-1}K^{-1}$
K_t	Thermal conductivity of receiver insulation, $Wm^{-1}K^{-1}$
l	Thickness of the receiver, m
Nu	Nusselt number
Pr	Prandtl number
Q_a	Absorbed solar energy, W
Q_l	Heat loss, W
$Q_{l,cd}$	Conductive heat loss, W

$Q_{l.cv}$	Convective heat loss, W
$Q_{l.r}$	Radiative heat loss, W
Q_u	Useful thermal energy, W
Re	Reynolds Number
T_a	Ambient temperature, K
T_r	Receiver Temperature, K
V_w	Wind speed, m/s
β	Volumetric coefficient of expansion for ambient air, K^{-1}
ϵ_a	Absorber emissivity
ϵ_{eff}	Effective emissivity
η_{en}	Thermal efficiency of dish
η_{opt}	Optical efficiency
σ	Stefan-Boltzmann constant, 5.67X10^{-8} $Wm^{-2}K^{-4}$
ν_{air}	Kinematic Viscosity of air, m^2s^{-1}

1. INTRODUCTION

Rapid degradation of fuel resources questions the survival of human beings on earth. Energy demand from the world is increasing day by day, which is expected to be doubled by the mid century. Due to these growing energy needs, usage of renewable energy resources is the favorable alternative.

Among renewable energy resources, solar energy has a pivotal role in providing energy as per demand. Among solar energy resources, energy that is produced through concentrated power is used in solar cooking, solar thermal power, solar water heating, etc. Concentrated solar technology is classified based on type of focus. Concentrators using line type receivers at their focus (called parabolic trough) and concentrators with cavity type receivers at their focal point (called solar parabolic dish). The parabolic dish consists of concentrator in the shape of a dish composed of reflective material which focuses sunlight on to the receiver at focal point.

A cavity type receiver is generally used, as it can improve intense flux absorption and minimise heat losses. These losses comprise of conductive loss through receiver wall and through insulation and convective, radiative loss from opening area of the receiver.

2. LITERATURE OVERVIEW

Safa Skouri [1] conducted experiments using four types of absorbers: flat plate, heat exchanger, water calorimeter and disk to determine the performance of solar parabolic concentrator. The thermal efficiency was observed to be varied between 40 and 77%.

Rafeu [2] conducted experiments using three distinct models to find the performance of the concentrator. For that they have used separate parameters for three models. These parameters are diameter of dish, aperture area of the concentrator, reflective material and focal point of the parabolic dish. From the experiments, it is observed that aluminium films are more effective than stainless steel and efficiency is over 60% with higher area of concentrator when compared with other two models. Shiva Gorjian [3] performed an experiment to find performance of solar steam generating system by point focus collector under different climatic operating conditions. About 250°C wall temperature is obtained for the receiver. From the obtained results, it is observed that performance of the system has lower value when the temperature of the absorber is higher. Convective heat loss of the receiver can be influenced by changing wind angle and velocity.

Ibrahim Laden Mohammed [4] has designed and developed a solar water heater by using a parabolic dish as a concentrator for producing water at 100°C. The heater shall provide a family of four with 40 litres of hot water a day. Tracking of the sun is done using linear actuator, which in turn eliminates human operator's need for constant monitoring. The system efficiency of about 52–56% was obtained. Raja Mohan [5] has done research which focuses on developing solar water heater system, which comprises of dish concentrator, conical absorber and water heater. He had performed experiments using parabolic dish along with conical absorber and also used conical absorber without parabolic dish. He obtained 65% efficiency with parabolic dish with conical cavity receiver and 41.04% without parabolic dish concentrator.

Yuting Tan [6] performed experiments to examine the thermal losses of semi-spherical shaped cavity type receiver using parabolic dish concentrator. Experiments for various inlet temperatures of 75–150°C and for different inclination angles of receiver from (0–90°C) were conducted. Also, changed the receiver aperture sizes and developed Nusselt number correlation, which is a function of Grashoff number for different operating conditions.

Jorge Alexander Alarcon [7] developed a solar parabolic dish collector prototype for rural areas in Columbia, where they have no access of electricity and even cannot afford to purchase gas (or) electric stove. For them, solar collector is a solution, where they can use thermal energy generated through sunlight for cooking.

Amos Veremachi [8] conducted experiments to find out the thermal performance of 2-m diameter point-focus solar collector with aluminium reflecting tiles having 0.9 reflectivity. Silicon carbide honeycomb is used as a receiver with atmospheric air as heat transfer fluid. Experiments are conducted with two different mass flow rates and obtained collector efficiency of 70%.

Siyoul Ryu and Taebeom Seo [9] performed experiments to assess heat losses from the receiver using two different receivers, which include conical shape (receiver-1) and combination of semi-circle and cylinder (receiver-2). In order to estimate the heat loss, they have investigated two parameters, namely, radiation properties and shape of the receiver. From the experimental results, they have concluded that receiver-1 is better than receiver-2. Jilte [10] did numerical three-dimensional analysis to examine the effect of receiver inclination angle on heat loss using seven different receiver shapes. Among the cavities investigated, spherical cavity has the highest convective loss and conical cavity produces lowest convective loss.

Atul A Sugade [11] conducted experiments to analyse effect of variation of flow rate on thermal performance of parabolic collector with truncated cone-shaped receiver made of copper. For best absorption, the receiver is coated with nickel chrome. From the experimental results, he found average collector efficiency as 68%.

Thirunavukkarasu [12] used receiver with hetero-conical cavity to investigate thermal efficiency of a parabolic dish collector by changing the rate of flow of working fluid. The parabolic dish which is used in the experiment is Scheffler type with multifaceted mirrors fitted on a parabolic frame. The efficiency of the system is 41%. Khaled Mahdi [13] assessed the thermal performance of a parabolic dish concentrator on production of steam utilizing cylindrical cavity receiver. Thermal efficiencies for the experiment were found to be about 40%.

3. DESCRIPTION OF THE EXPERIMENTAL TEST SET-UP

Figure 1 displays the point focus solar collector system, which consists of parabolic dish reflector and cavity receiver. The aim of this project is to analyze the thermal efficiency of solar parabolic dish concentrator using dome cylindrical type cavity receiver. The concentrator which is a parabolic dish used to concentrate the incident radiation from the sun on to the

receiver located at the focus of the dish. At the focal point of dish, helical coiled receiver is placed, which receives and converts the concentrated solar energy into thermal energy.

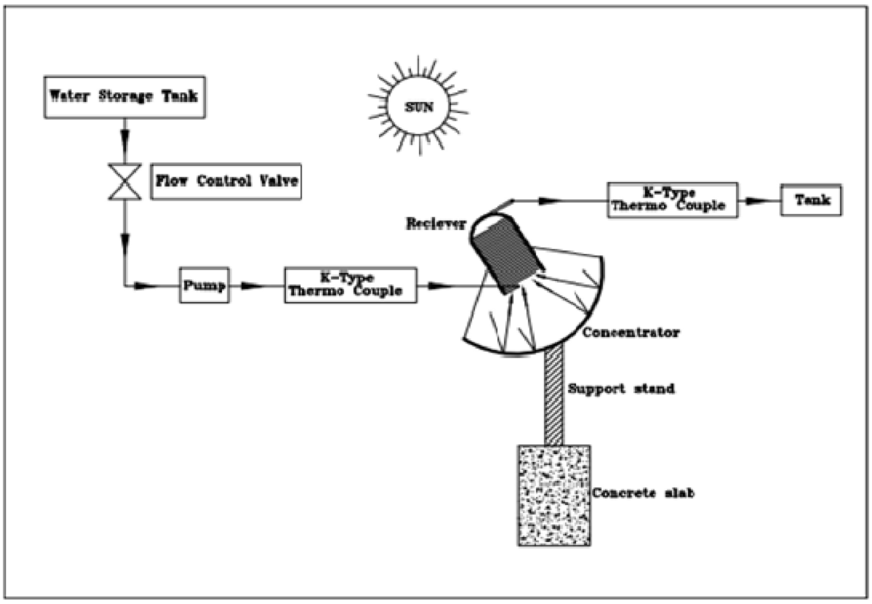

Figure 1: Schematic of Experimental Test Set Up.

3.1 Concentrator

Flat plate collectors are generally one dimensional. Parabolic troughs with focus on a line are two dimensional, whereas parabolic dish concentrators with focus as a point are three dimensional.

Figure 2: Dish Concentrator.

In the present work, the parabolic dish used is of 1.3 m in diameter. Solar parabolic dish, which is to be used for the experiment is cost effective. The reduction in system cost becomes conceivable by utilizing an obsolete satellite dish antenna. An outdated dish made up of aluminium surface is taken from “RF and Microwave Research Centre" in KLEF (Deemed-to-be-University).

3.2 Reflector

Parabolic dish should contain a reflective material so as to concentrate solar energy on to the receiver. Low iron glass mirror of 2 mm thick, which is coated with silver at its back, provides less weight to glass. These mirrors got fitted to parabolic dish with the help of glue.

Figure 3: Reflective Mirror.

3.3 Receiver

The receiver that is used in this work is a helical coiled dome-cylindrical shaped cavity receiver made of copper. The receiver has a diameter of 150 mm at the aperture and a total length of 200 mm, as shown in figure 4. Copper coil has a diameter of 8 mm.

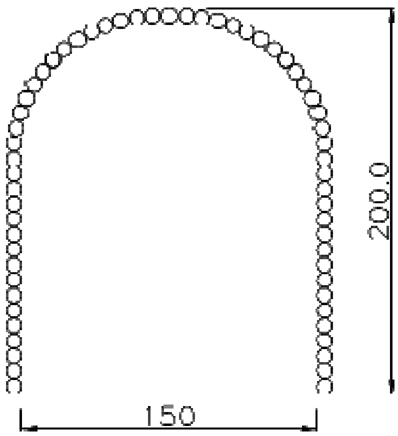

Figure 4: Schematic of Receiver.

Figure 5: Photograph of Receiver.

3.4 Insulation

Ceramic wool is furnished on outer surface of the receiver which acts as the thermal insulation.

Figure 6: Receiver Covered with Insulation.

3.5 Parameters Used for the Experimentation

Parabolic concentrator directs low density incident solar radiation on to a small area of the receiver. The most significant parameters that maximizes the amount of energy that is to be concentrated on to the receiver are: Reflective material on the concentrator, projected area of the concentrator and accuracy of mirror making. Larger the mirror area, greater the weight of the collector system. Receiver winded with insulating material placed at the focal point projects its shadow on to the concentrator, which in turn reduces the amount of solar radiation entering the receiver; therefore, thickness of insulation should not be increased. Table 1 shows various parameters that are used in the experiments.

Table 1: Parameters Used in the Experiments

Sl. No.	Description	Value
1	Parabolic dish diameter	1.3 m
2	Aperture area of parabolic dish collector	1.1304 sq. m
3	Reflectivity of silver coated low iron glass mirror	0.85
4	Thickness of mirror (glued on the concentrator)	2 mm
5	Diameter of receiver at bottom	0.15 m
6	Surface area of receiver	$0.1295 m^2$
7	Thickness of insulation	10 cm
8	Thermal conductivity of copper	384 (W/m.K)
9	Density of copper	8900 (kg/m^3)
10	Melting point of copper	1083 (°C)

4. EXPERIMENTAL INVESTIGATIONS

In the present study, experiments are conducted on two clear sunny days in the month of April. Schematic layout of heat transfer fluid circulation in the experimental set-up with line diagram is presented in Figure 1. It consists of a dome-cylindrical-shaped cavity receiver placed at focal point of a parabolic dish concentrator, concentrator with receiver cemented on a concrete slab with a support stand. The receiver is placed at an angle of 90° with the concentrator, i.e., perpendicular to the surface of the concentrator as to absorb total radiation that is reflected from the dish.

The working fluid used in the present experiment is water. This working fluid is circulated to the receiver from water storage tank though a pipe. In order to measure the flow of the working fluid, we have used flow control valve control. The working fluid enters from bottom of the receiver, runs through the receiver and leaves from the top. It was done to make sure that the higher temperatures will be at the top portion of the receiver and lower temperatures at the base

of the receiver. K-type thermocouples are used to measure temperatures of working fluid at inlet, outlet and on the surface of the receiver. The flow was kept unchanged on a given day for the entire period of an experimental phase. The water exiting from the receiver was sent off to the drain without circulating back to the inlet water storage tank.

The temperatures of receiver and working fluid was measured for every 10 minutes, and the experiments lasted until the solar radiation was available at adequate intensity.

5. MATHEMATICAL FORMULATION

In this section, basic equations for evaluating the performance are given. The solar energy absorbed Q_a by solar parabolic dish receiver is given by [14]:

$$Q_a = G^* A_a \eta_{opt} \tag{1}$$

Useful thermal energy Q_u can be determined as:

$$Q_u = Q_a - Q_l \tag{2}$$

$$Q_l = Q_{l,cv} + Q_{l,r} + Q_{l,cd}. \tag{3}$$

Heat losses from the receiver occur due to the temperature difference between the receiver and the ambient air. In the present work, heat losses in the receiver are categorized as convective loss $Q_{l,cv}$, conductive loss $Q_{l,cd}$ and radiative loss $Q_{l,r}$.

Conductive heat loss from the receiver can be obtained from the following equation [15]:

$$Q_{l,cd} = [(1/\,(1/A_o h_w)) + (1/\,k_t (A_0 A_w)^{1/2})]\,(T_r - T_a) \tag{4}$$

The following equation proposed by Hilpert (1933) [16] for flow across a pipe is used to determine the outside convective heat transfer coefficient of wind h_w.

$$\overline{Nu_D} = \frac{h_w\, d}{K_{air}} = C\,(Re_D)^n Pr^{1/3}, \tag{5}$$

where constants C and n are given in the following table:

Table 2

Re	C	n
0.4 to 4	0.989	0.330
4 to 40	0.911	0.985
40 to 4000	0.683	0.466
4000 to 40000	0.193	0.618
40000 to 400000	0.027	0.805

Equation for Newton's Law of cooling is used to calculate the convective losses $Q_{l,cv}$ of the receiver.

$$Q_{l,cv} = h_{cv} A_c (T_r - T_a) \tag{6}$$

$$h_{cv} = h_n + h_f \tag{7}$$

Robert proposed a relation to find the forced convection heat loss coefficient [17].

$$h_f = 0.196 V_w^{1.849} \tag{8}$$

$$h_n = (Nu K_{air})/d \tag{9}$$

Modified Clausing model correlation [18] is used to calculate Nusselt number for natural convection heat loss:

$$Nu = 0.082[Gr.\ Pr]^{(1/3)}[-0.9+2.4(T_r/T_a)-0.5(T_r/T_a)^2.Z(Z_w)] \tag{10}$$

where $Gr = g\beta(T_r - T_a)d^3/\nu^2$

Z_w is the receiver's tilting angle.

Radiation losses $Q_{l,rad}$ of receiver system are given by the following equation [19]:

$$Q_{l,rad} = \epsilon_{eff}\sigma A_c(T_r^4 - T_a^4) \tag{11}$$

$$\epsilon_{eff} = 1/[1 + (1/(1 - \epsilon_a))(A_{ab}/A_c)] \tag{12}$$

The thermal efficiency of the concentrator η_{en} is defined as the ratio between the useful thermal energy and direct solar radiation incident on the collector:

$$\eta_{en} = Q_u/I^* \tag{13}$$

where direct solar radiation I^* is the difference between global radiation G^* and diffuse radiation D^*.

6. RESULTS AND DISCUSSIONS

Experiments were carried out for two different flow rates of water at 0.0035 kg/s and 0.0065 kg/s to find the thermal performance of solar parabolic dish with dome-cylindrical cavity receiver.

Table 2 shows the water inlet, outlet, ambient and average receiver temperatures for the water flow rate at 0.0035 kg/s. Total heat gain, heat losses and collector efficiency were obtained from Eqs. (2), (3) and (13), respectively.

Table 3: Experimental Results for Mass Flow Rate of Water at $\dot{m}$ = 0.0035 kg/s

Time	T_{in} (°C)	T_{out} (°C)	T_{amb}(°C)	Average Receiver Temp. (°C)	Optical Energy Captured Receiver(W)	Overall Heat Loss from the Receiver (W)	Heat gain by Water (W)	Efficiency of the Concentrator (%)
10:15 AM	33.5	53	37	56.4	384	47	337	57
10:25 AM	33	52	38	55	384	41	346	59
10:35 AM	33	53	39	55.2	384	39	344	59
10:45 AM	33	52	39	56.1	384	41	343	58
10:55 AM	33	61.5	40	64.1	384	60	324	55
11:05 AM	33	55	40	61.8	384	54	331	56
11:15 AM	33	56	40	61.3	384	52	332	57
11:25 AM	33	57	40	62.6	384	56	328	56
11:35 AM	33	60	37	64	384	69	325	55
11:45 AM	33	60	40	65	384	63	322	55

From table 3, average inlet, outlet, ambient temperature of water and average receiver temperatures are observed to be 33.05°C, 55.95°C, 39°C and 60.15°C, respectively. The average efficiency of collector is 57%.

Table 4 shows the water inlet, outlet, ambient and average receiver temperatures for the water flow rate at 0.0065 kg/s. Total heat gain, heat losses and collector efficiency were obtained from Eqs. (2), (3) and (13), respectively.

Table 4: Experimental Results for Mass Flow Rate of Water at $\dot{m}$= 0.0065 kg/s

Time	T_{in}(°C)	T_{out} (°C)	T_{amb} (°C)	Average receivertemp. T_r(°C)	Optical Energy Captured Receiver(W)	Overall Heat Loss from the Receiver (W)	Heat Gain by Water (W)	Efficiency of the Concentrator (%)
10:15 AM	32	42	36	51	384	33	351	60
10:25 AM	32	46	36	50	384	31	353	60
10:35 AM	32	44	38	51	384	29	356	61
10:45 AM	32	46	38	49	384	24	360	61
10:55 AM	32	49	38	55	384	38	346	59
11:05 AM	32	47	38	51	384	29	356	61
11:15 AM	32	50	36	54	384	41	343	59
11:25 AM	32	45	36	49	384	29	356	61
11:35 AM	32	51	36	53	384	38	346	59
11:45 AM	32	42	36	53	384	38	346	59

From table 4, average inlet, outlet, ambient temperature of water and average receiver temperatures are observed to be 32°C, 46.2°C, 36°C and 52°C, respectively. The average efficiency of collector is 60%.

6.1 Variation of Average Receiver Temperatures with Different Flow Rates of Water

Thermal efficiency of parabolic concentrator was observed to be dependent on temperature of the receiver and intensity of incident radiation. Average receiver temperature was observed to be 60.15°C for the flow rate 0.0035 kg/s. Mean receiver temperature was observed to be dependent on the intensity of solar radiation and wind velocity as well.

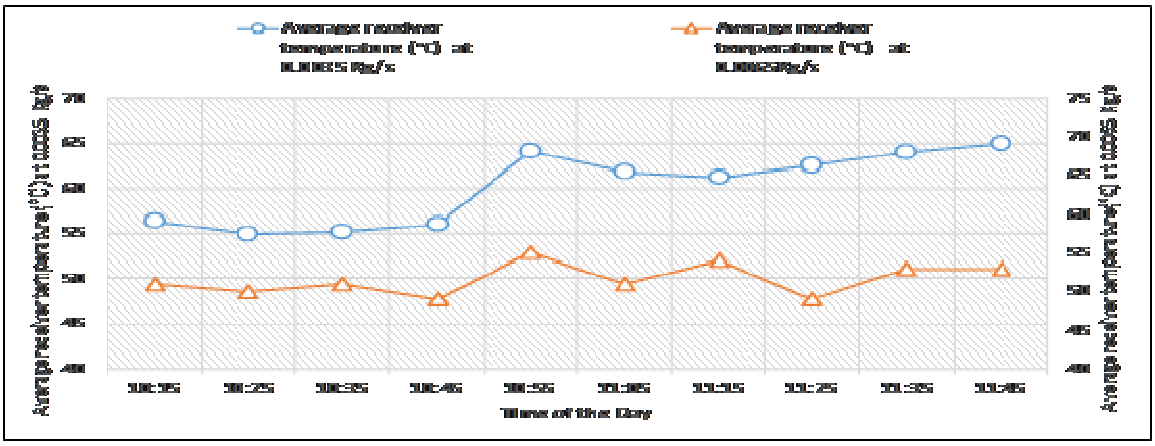

Figure 7: Variation of Average Temperatures of the Receiver with Different Water Flow Rates.

Figure 7 illustrates that the temperature of receiver will rise with reduction in mass flow rate (0.0035 kg/s) of water when compared to higher flow rates (0.0065 kg/s). As stated, the average temperature of the receiver is higher for reduced rate of flow of water at (0.0035 kg/s) and it is about 60.15°C, which is higher than that of rate of flow of water at (0.0065 kg/s) with 52°C. It was observed that the temperature of the receiver with reduced flow rate rises by 15.67%.

6.2 Variation in Water Temperature at Outlet with Different Flow Rates

Outlet water temperatures for different flow rates were plotted in Figure 8. Water temperature at outlet relies on the receiver's temperature. It is observed that water outlet temperature for the mass flow rate of 0.0035 kg/s increased for the first 20 minutes and then got reduced due to cloud cover and got stabilized at the end of the experiment. The maximum outlet temperature of around 61.5°C is obtained when the ambient temperature is about 33°C. During the experiment, the mean difference in temperature between outlet and inlet temperature reaches 28.5°C. This water temperature can be used for water desalination and solar cooking.

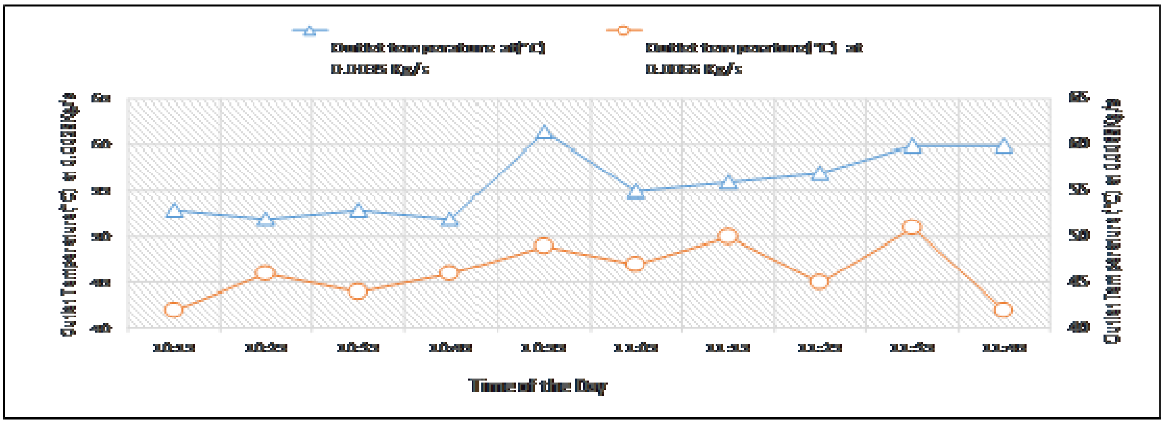

Figure 8: Variation of Outlet Temperatures with Different Flow Rates of Water.

Figure 8 illustrates the variation in the water outlet temperature of with different flow rates. From the figure, it is clear that with increased water flow rate the water temperature coming out of the receiver gets decreased, as compared to the lower flow rate. There will be increase in the water temperatures at the outlet, when there is increase in the receiver temperature. The average water outlet temperature at 0.0035 kg/s is 21.1% higher than that of water outlet temperature at flow rate of 0.0065 kg/s.

6.3. Variation of Overall Heat Losses with Various Mass Flow Rates of Water

Heat losses are caused by temperature difference between receiver and the environment surrounding the receiver. Also, depends on geometry of the receiver and geometry of the concentrator. The receiver's conductive heat loss is caused through insulation material that is wrapped around copper tubes. Heat loss in receiver due to convection depends on inclination angle of receiver, internal surface area of the receiver and wind velocity. Heat loss due to convection is low as receiver is placed at 90^0 with the concentrator and also wind velocity is low throughout the experiment. Heat losses due to radiation from the receiver are due to emissions from the surface.

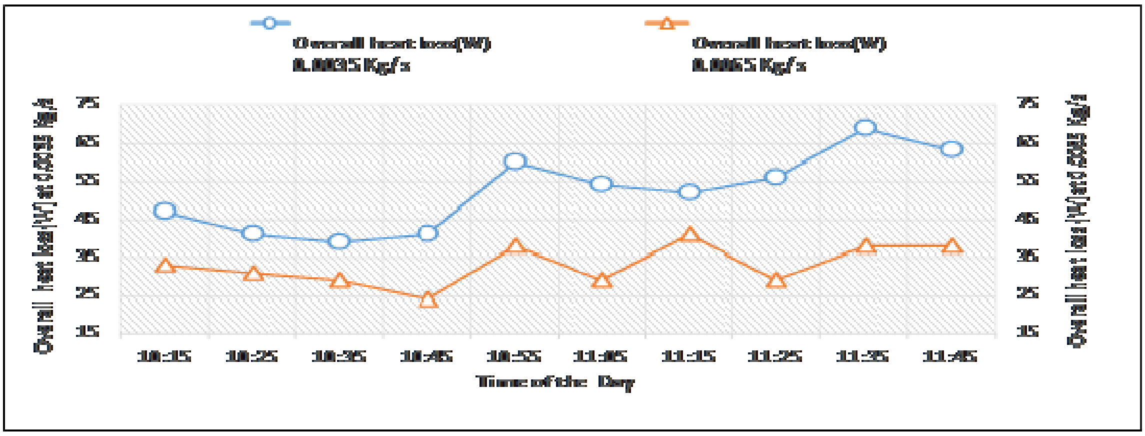

Figure 9: Variation of Heat Loss with Different Flow Rates of Water.

Figure 9 depicts the variation of total heat losses with different mass flow rates of water. For reduced water flow rate (0.0035 kg/s), heat loss was observed to have been increased, as compared to the increased flow rate (0.0065 kg/s). Average heat loss of 52 W and 33 W has been obtained with flow rates 0.0035 kg/s and 0.0065 kg/s, respectively. With increased water flow rate, there is 36.54% decrease in heat loss.

6.4 Variation of Heat Gain by Water with Different Flow Rates

Heat gain or useful thermal energy is the difference between absorbed energy and losses. Useful heat energy depends on receiver temperature, wind velocity and intensity of solar radiation. As receiver temperature increases, the thermal conductivity of air around the receiver increases. Heat gained by working fluid gets reduced with increase in heat losses due to air surrounding the receiver.

Figure 9 shows the effect of average temperature of the receiver on heat gain by water at flow rate of 0.0035 kg/s.

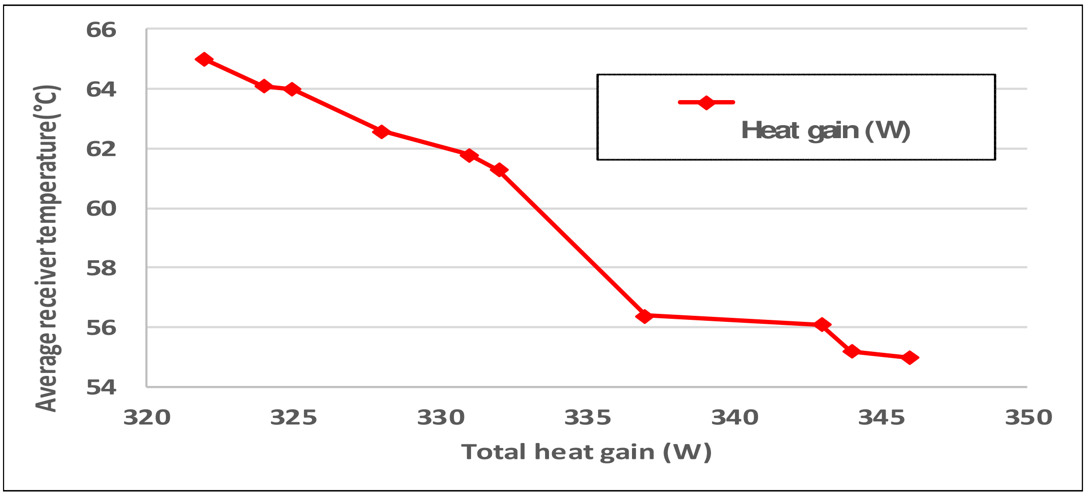

Figure 10: Variation of Heat Gain with Average Temperature of Receiver.

From figure 10, it is observed that as temperature of the receiver increases, the amount of heat nergy gained by water reduces. Heat gained by water is obtained at a maximum of 346 W at 55°C of receiver temperature and minimum of 322 W at 65°C.

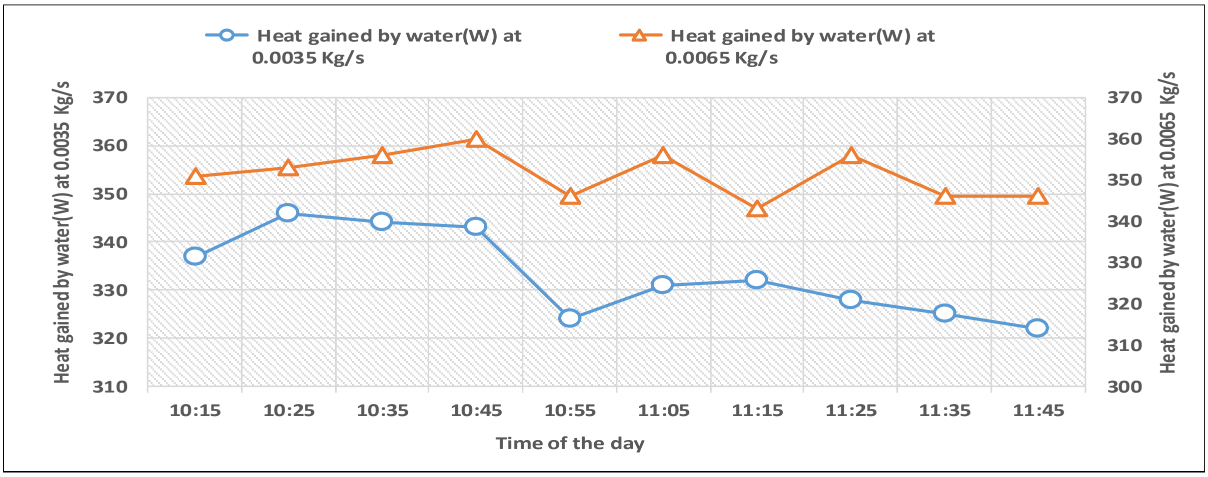

Figure 11: Variation of Heat Gain with Various Flow Rates of Water.

Figure 11 illustrates heat gained by water with different flow rates. From figure 11, it is observed that with increased flow rate, the amount of heat gained by water gets increased. The maximum amount of heat gained is about 360 W at 49° C of receiver temperature for the flow rate of 0.0065 kg/s.

6.5 Variation in efficiency of Collector with Different Flow Rates

The main aim of this experiment is to find the thermal efficiency of solar parabolic dish. Collector efficiency is the ratio of useful thermal energy to direct solar radiation. Higher flow rate of water leads to higher thermal efficiency. Higher flow rate makes the flow more turbulent and so the transfer of heat between the receiver and the fluid is reduced.

This results in the receiver to become colder and to have lower thermal losses, the fact that increases the thermal efficiency**.**

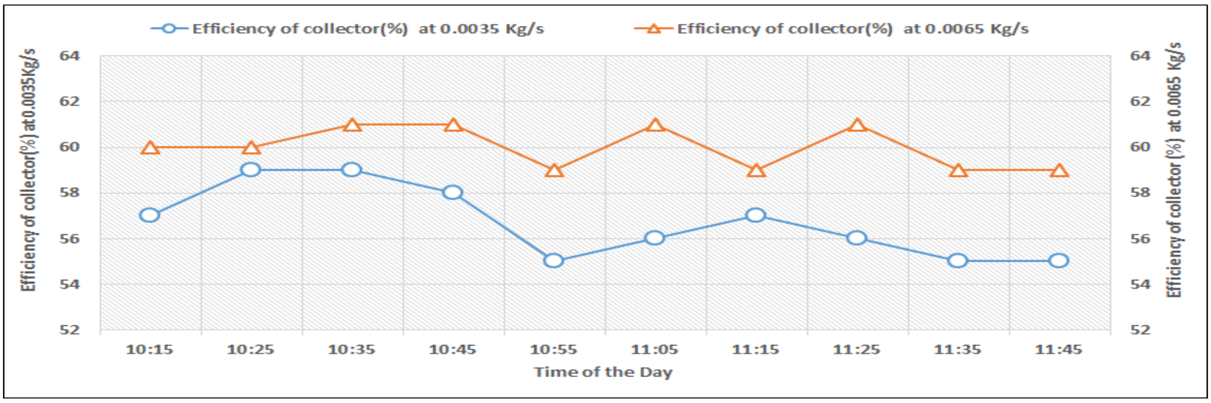

Figure 12: Variation in Efficiency of Collector with Different Flow Rates of Water.

Figure 12 depicts the efficiency of the collector for two different mass flow rates of water. From graph, it can be seen that as mass flow rate of water increases, collector efficiency also increases. For the flow rate of 0.0065 kg/s, collector efficiency obtained a maximum of 61%.

7. CONCLUSIONS

An experimental study was conducted with different flow rates of working fluid (water) to determine the efficiencies of dome cylindrical cavity receiver with parabolic dish concentrator. It was found that thermal efficiency depends primarily on receiver temperature and radiation intensity. Heat loss from the receiver affects the system performance.

As discussed earlier, receiver temperature has a vital role in finding the efficiency of the system. From the results obtained through the experiments, it is observed that the receiver's average temperature obtained is 60.15°C maximum, for reduced flow rate of water at 0.0035 kg/s. It was observed that the receiver temperature with reduced flow rate rises by 15.67%. With increase in average receiver temperature, outlet temperature also increased and obtained a maximum of 61.5°C for the mass flow rate of 0.0035 kg/s. The average temperature of water at outlet is 55.95°C at the mass flow rate of 0.0035 kg/s, which is 21.1% higher than that of water temperature with mass flow rate of 0.0065 kg/s. With increase in receiver temperatures, heat losses got increased due to differences in temperature between receiver and surroundings, thereby reducing the efficiency.

Average heat loss of 52 W and 33 W has been obtained with mass flow rates 0.0035 kg/s and 0.0065 kg/s, respectively. With increased flow rate of water, there is 36.54% decrease in heat loss. With reduced heat loss, the amount of heat gained got increased and obtained a maximum of 360 W at 49°C of receiver temperature for the mass flow rate of 0.0065 kg/s. It is observed that the overall system efficiency is 61%, which is obtained for the flow rate of 0.0065 kg/s.

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